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(54) **ECONOMICAL CORE DESIGN FOR ELECTROMAGNETIC DEVICES**

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H01F 17/04 (2006.01)

(52) **U.S. Cl.**
USPC **336/216**; 336/212; 336/217; 336/218; 336/221

(58) **Field of Classification Search**
USPC 336/212, 216–218, 234
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

2,300,964 A * 11/1942 Putman 336/217
2,647,575 A * 8/1953 Patterson 83/679
2,989,712 A * 6/1961 Krabbe 336/217
3,129,377 A * 4/1964 Monroe et al. 363/154
3,157,850 A * 11/1964 Winter et al. 336/216
3,169,236 A * 2/1965 McQuade 336/218
3,183,461 A * 5/1965 Tipton 336/60
3,200,358 A * 8/1965 Neydli 336/217
3,457,635 A * 7/1969 Michiulis 29/609
4,520,556 A * 6/1985 Pasko et al. 29/606
5,371,486 A * 12/1994 Yamada et al. 336/212
5,777,537 A * 7/1998 Allen et al. 336/96
6,100,783 A * 8/2000 Hopkinson et al. 336/216
2006/0226947 A1* 10/2006 Pauley et al. 336/234

* cited by examiner

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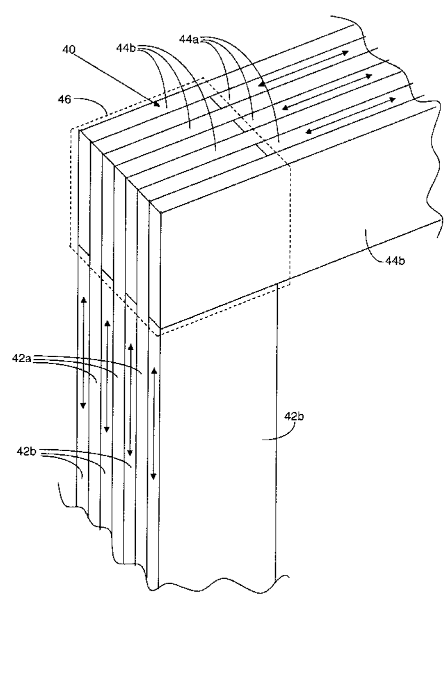
(57) **ABSTRACT**

A magnetic core for an electromagnetic device is formed from alternating interleaved steel laminations. The core comprises a plurality of core elements comprising legs and yokes oriented substantially quadrature to the legs, such that abutting core elements are in substantially quadrature relation. A plurality of flux deflection zones are defined in regions where flux flows from one core element to an abutting core element. At least one of the layers has at least one core element composed of grain-oriented steel, and the remaining core elements are composed of non-grain-oriented steel, such that at least some flux deflection zones are composed of a substantial amount or substantially entirely of non-grain-oriented steel. Flux flowing in the direction of the grain orientation in the core element(s) composed of grain-oriented steel changes direction to flow through the abutting core element in the flux deflection zone composed of non-grain-oriented steel. This reduces the power losses in flux deflection zones of the core relative to cores formed entirely from grain-oriented steel, because the flux is never flowing perpendicular to the direction of the grains in the steel, while providing a design that is considerably less expensive than cores formed from non-grain-oriented steel with substantially the same level of power losses or lower.

20 Claims, 9 Drawing Sheets



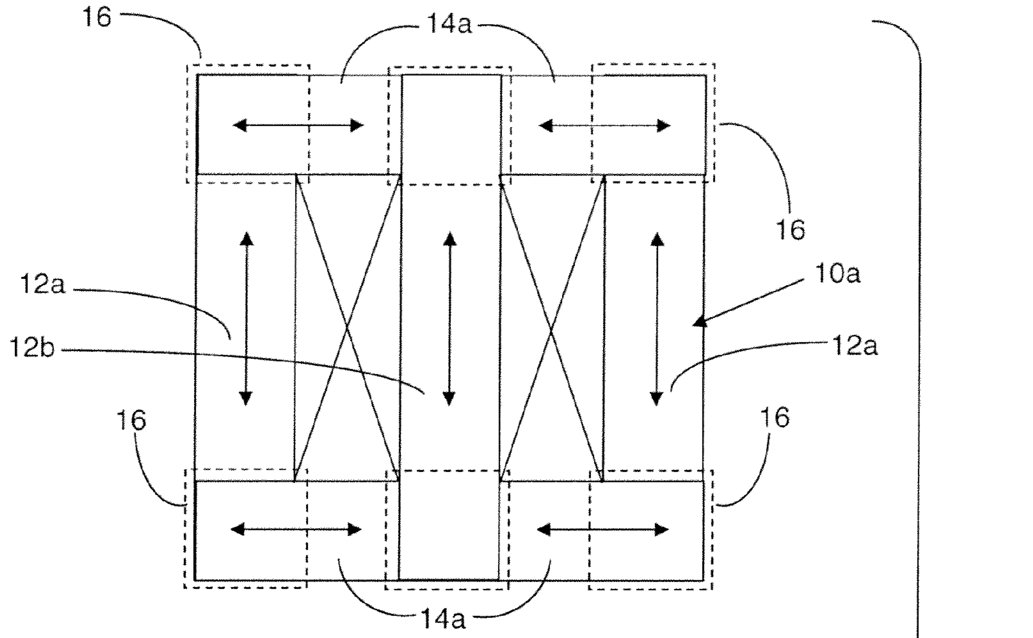


Fig. 1A
PRIOR ART

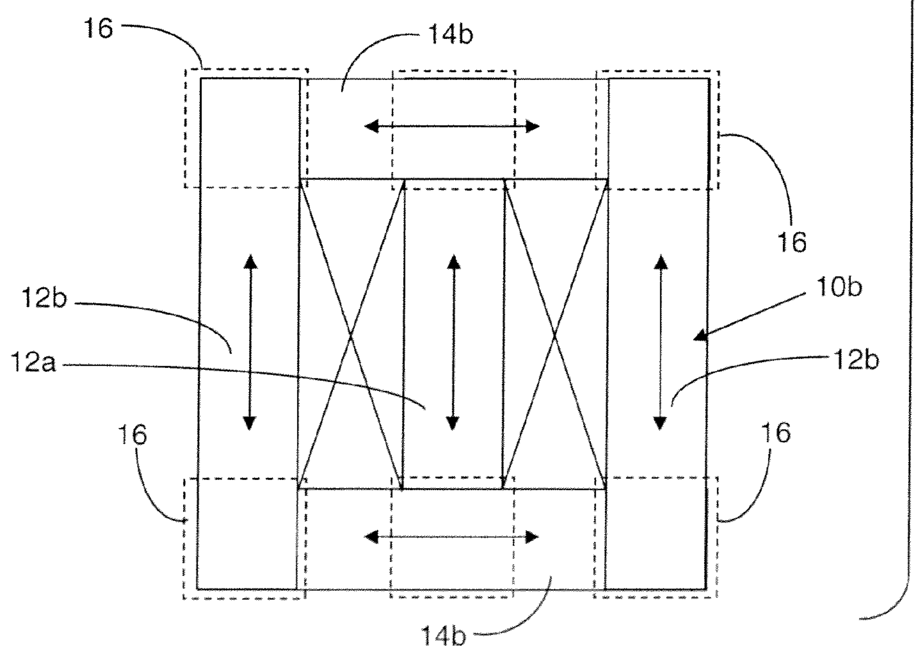


Fig. 1B
PRIOR ART

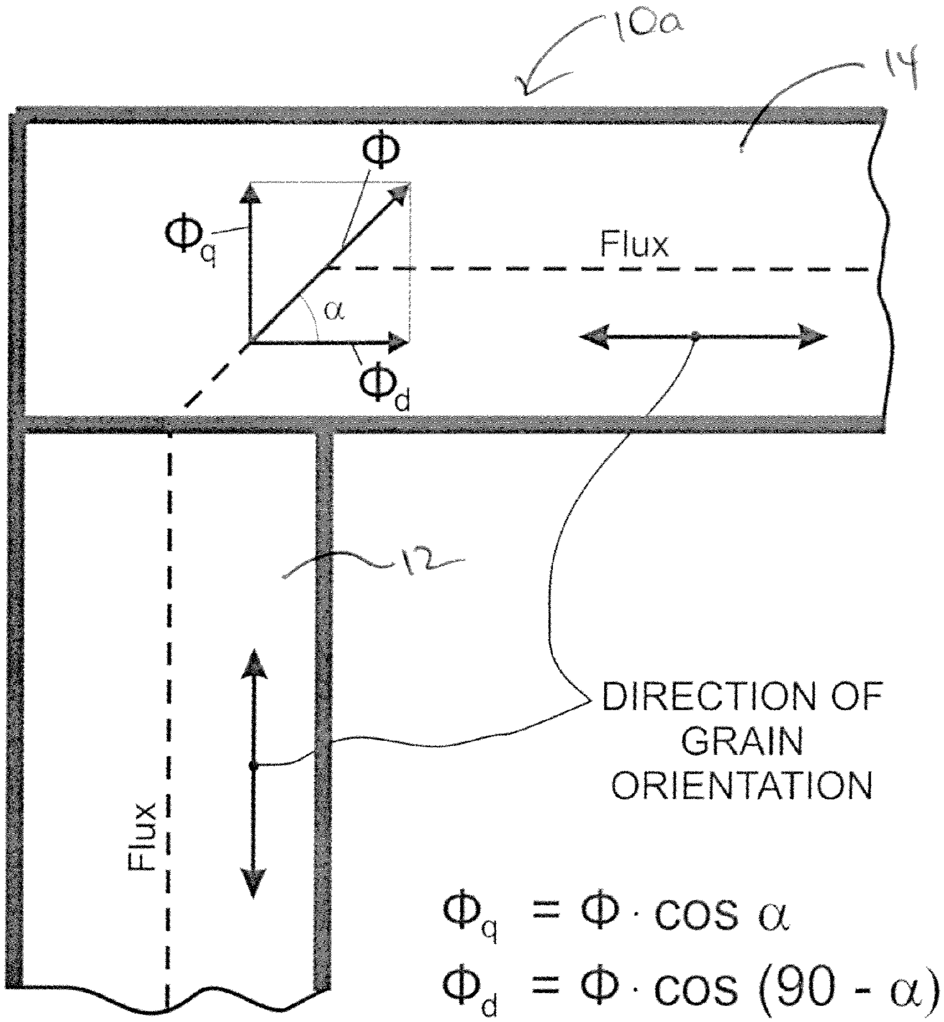

10a
14
Φ
Φ_q
Flux
α
Φ_d
12
DIRECTION OF GRAIN ORIENTATION
Flux
$\Phi_q = \Phi \cdot \cos \alpha$
$\Phi_d = \Phi \cdot \cos (90 - \alpha)$

Fig. 2

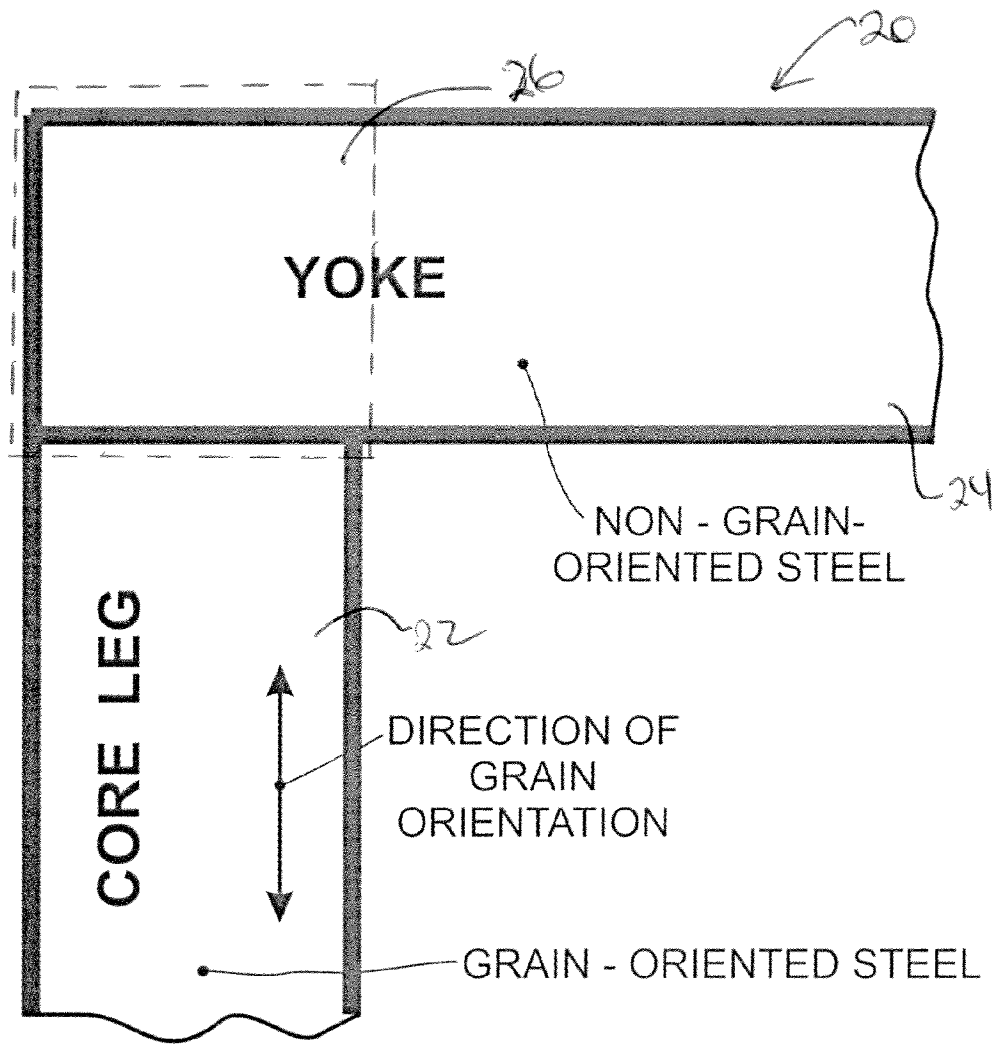

20
26
YOKE
24
NON - GRAIN-
ORIENTED STEEL
22
CORE LEG
DIRECTION OF
GRAIN
ORIENTATION
GRAIN - ORIENTED STEEL

Fig. 3A

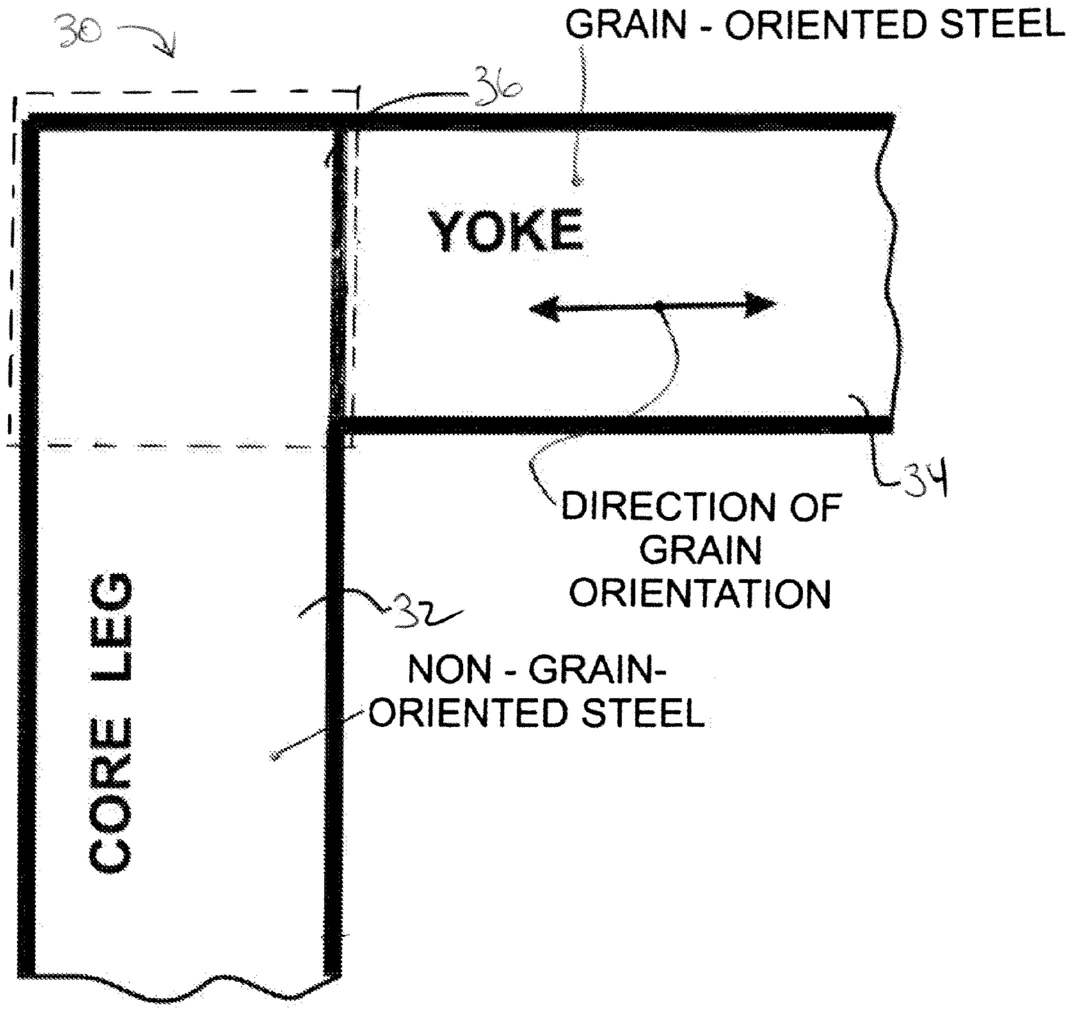

30
GRAIN - ORIENTED STEEL
36
YOKE
34
DIRECTION OF GRAIN ORIENTATION
CORE LEG
32
NON - GRAIN-ORIENTED STEEL

Fig. 3B

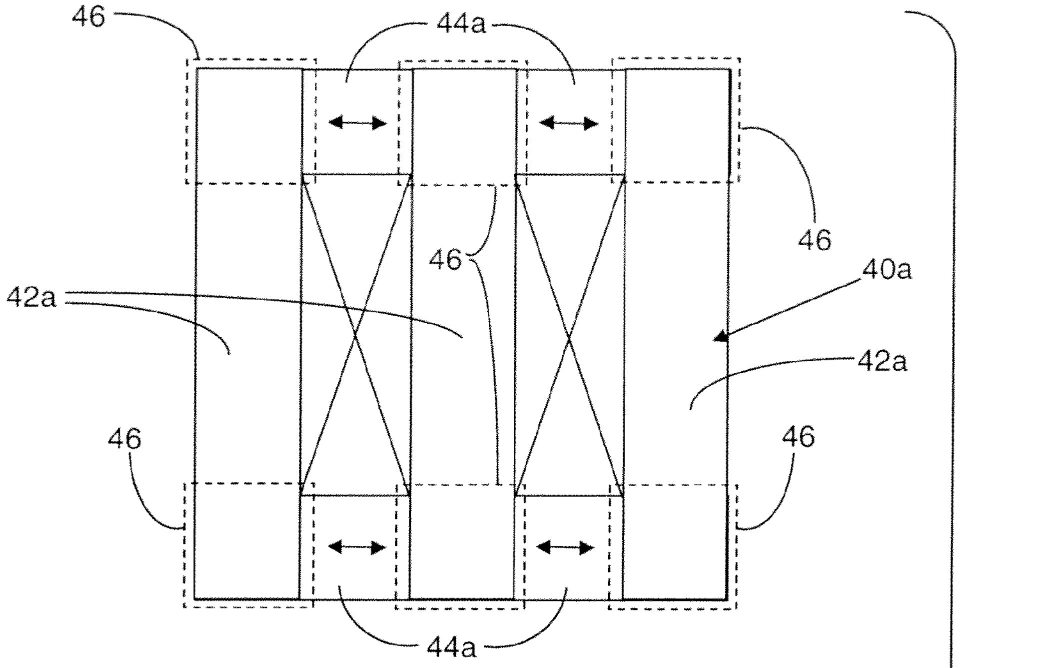

46
44a
46
46
46
42a
40a
42a
46
46
44a
40

Fig. 4A

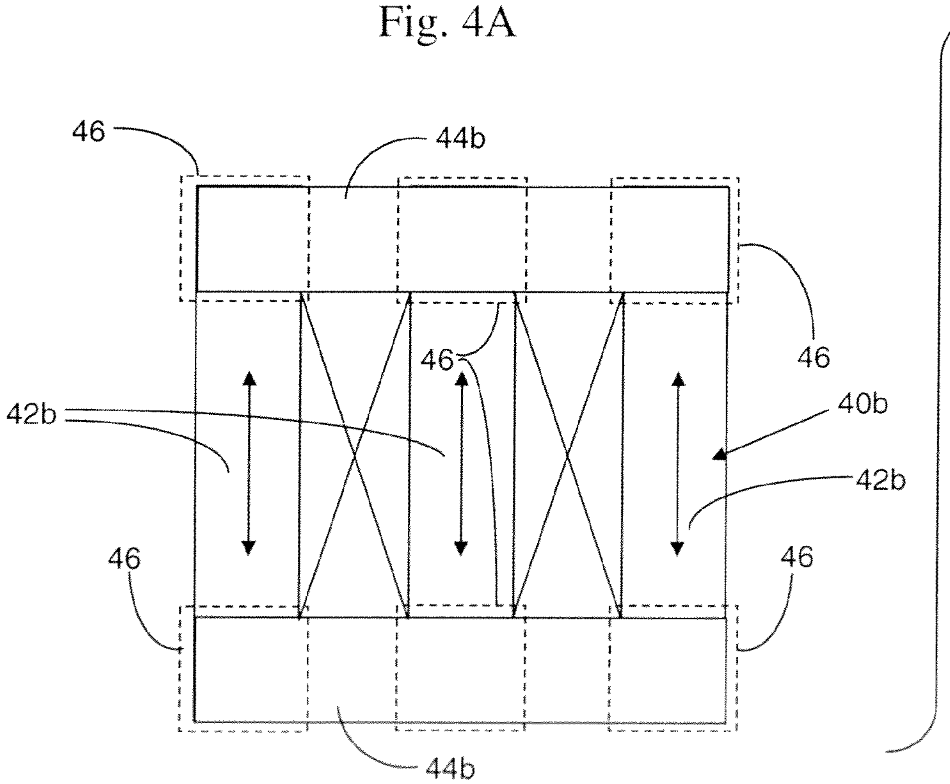

46
44b
46
46
42b
40b
42b
46
46
44b

Fig. 4B

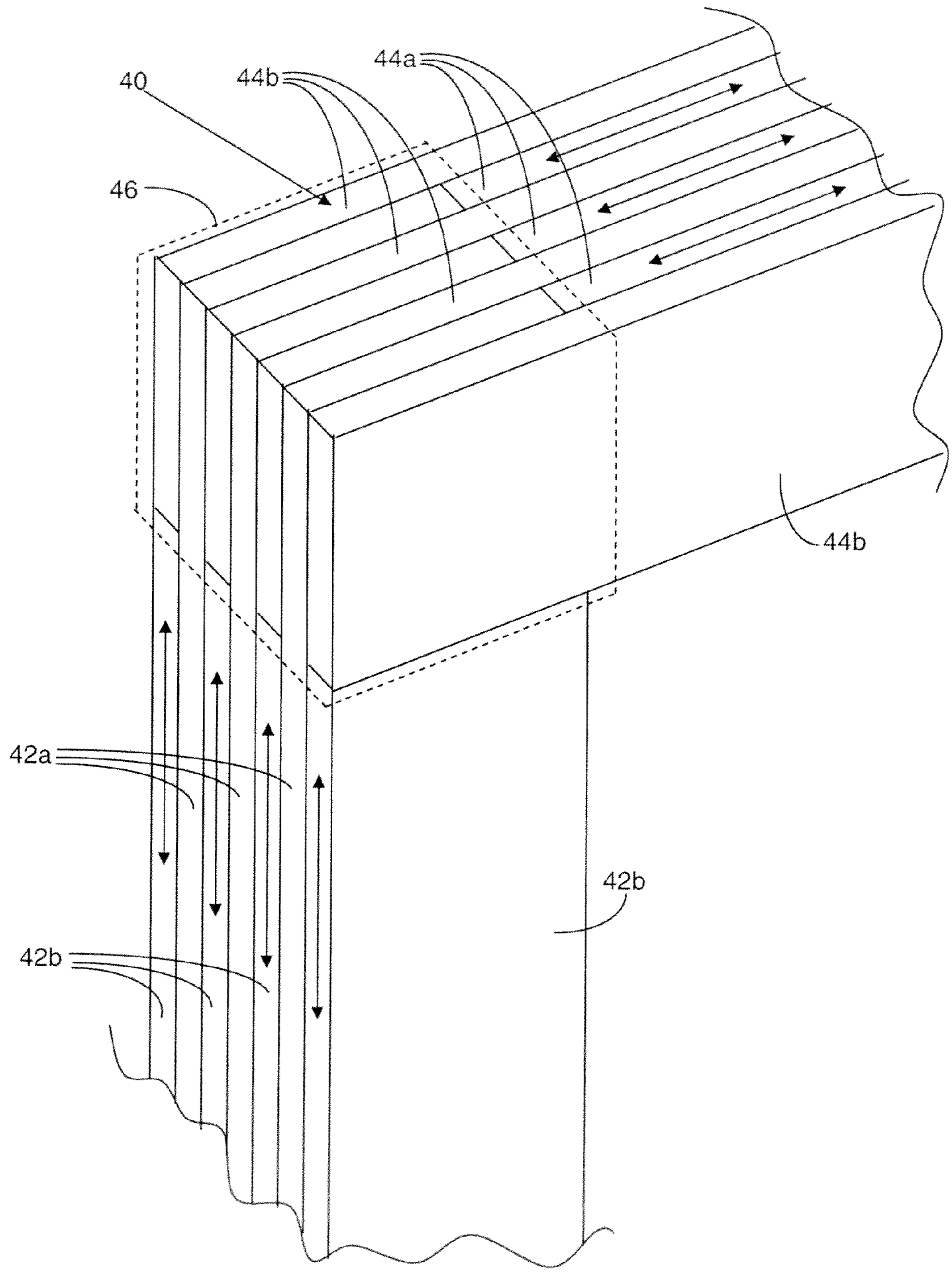


Fig. 4C

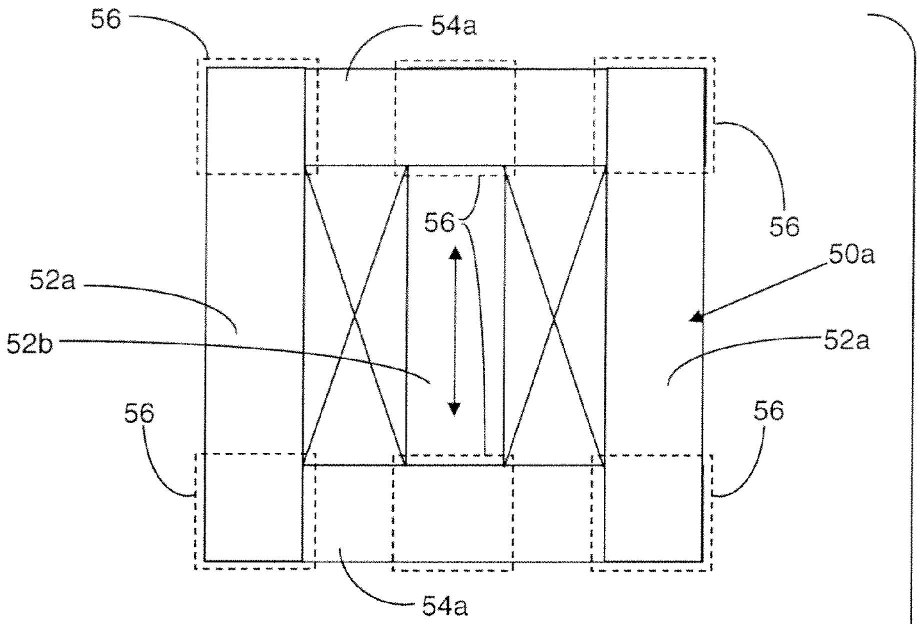

56
54a
56
56
50a
52a
52b
52a
56
56
54a

Fig. 5A

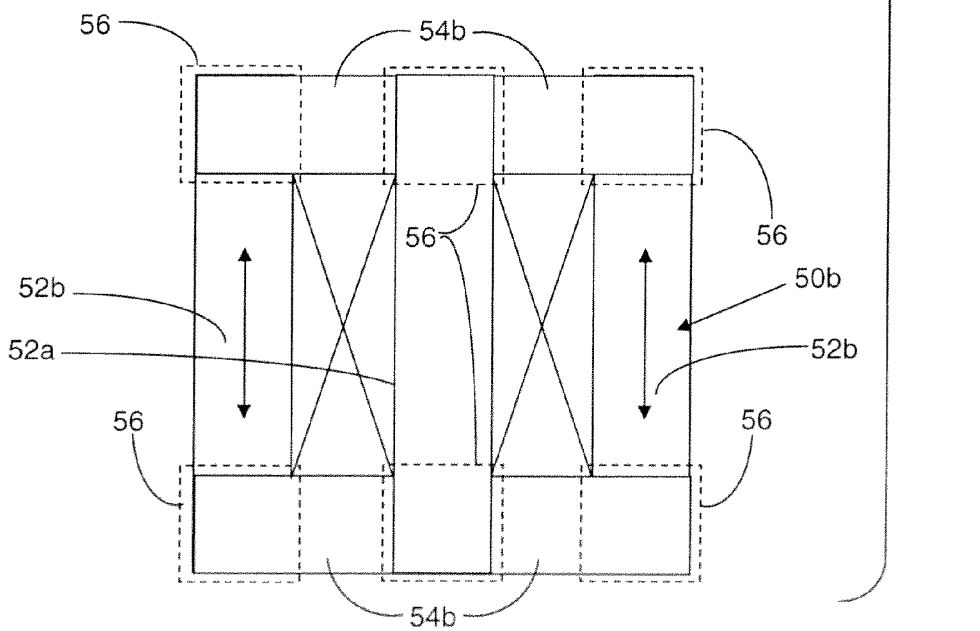

56
54b
56
56
50b
52b
52a
52b
56
56
54b
50

Fig. 5B

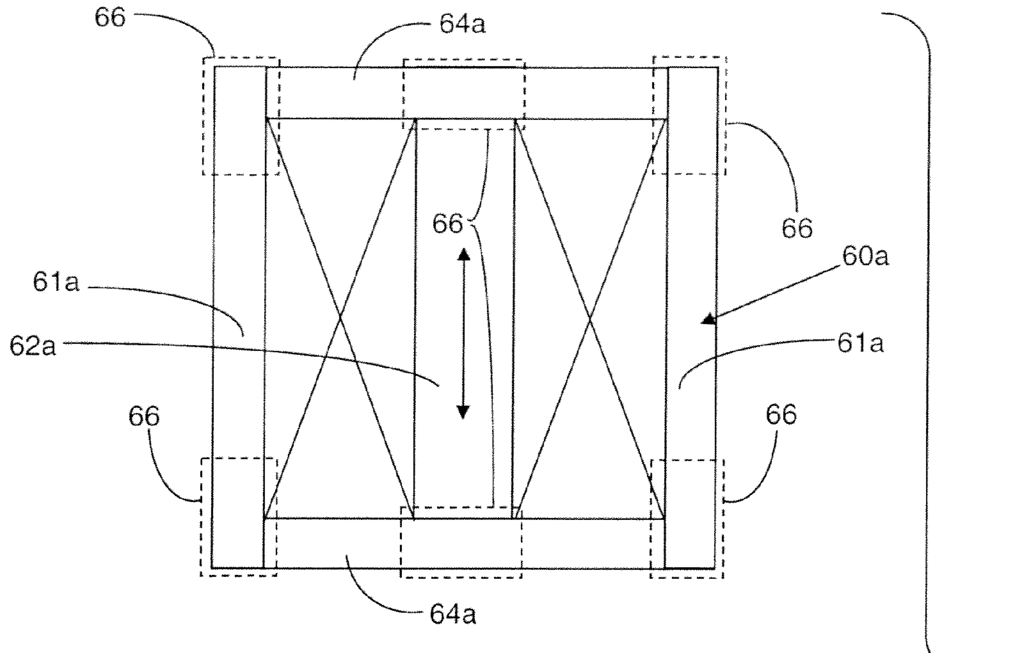

66
64a
66
66
60a
61a
62a
61a
66
66
64a
60

Fig. 6A

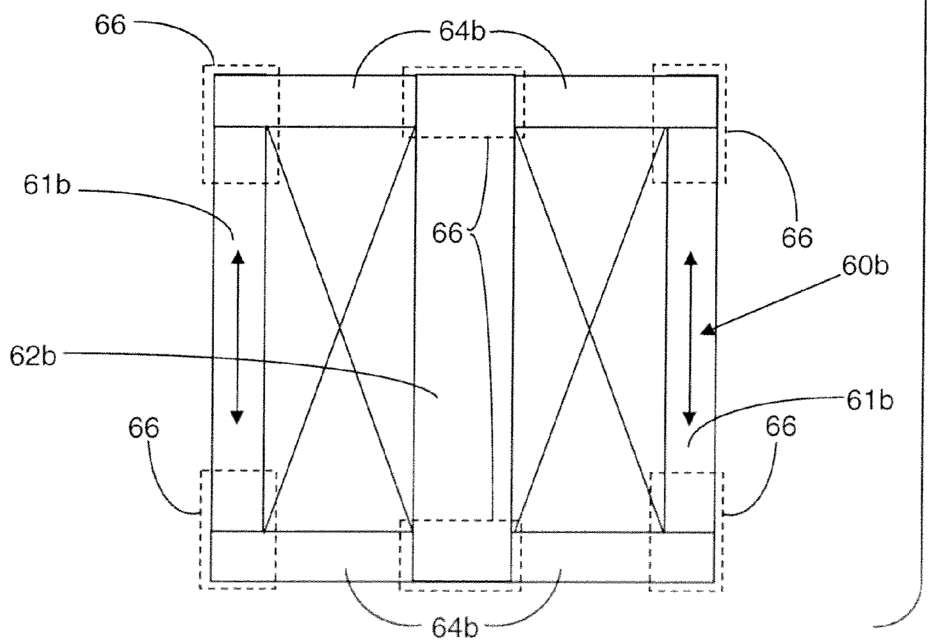

66
64b
61b
66
66
60b
62b
61b
66
66
64b

Fig. 6B

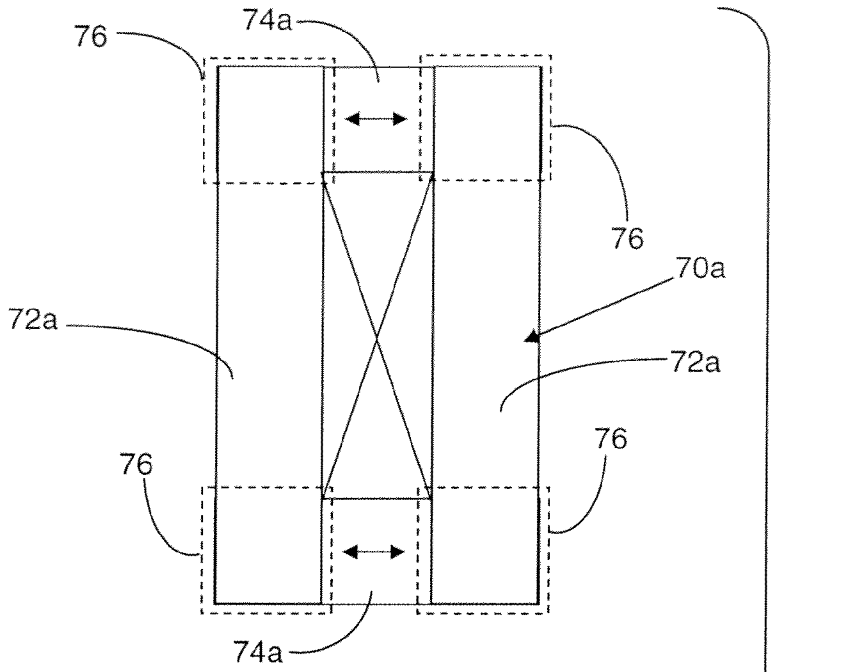


Fig. 7A

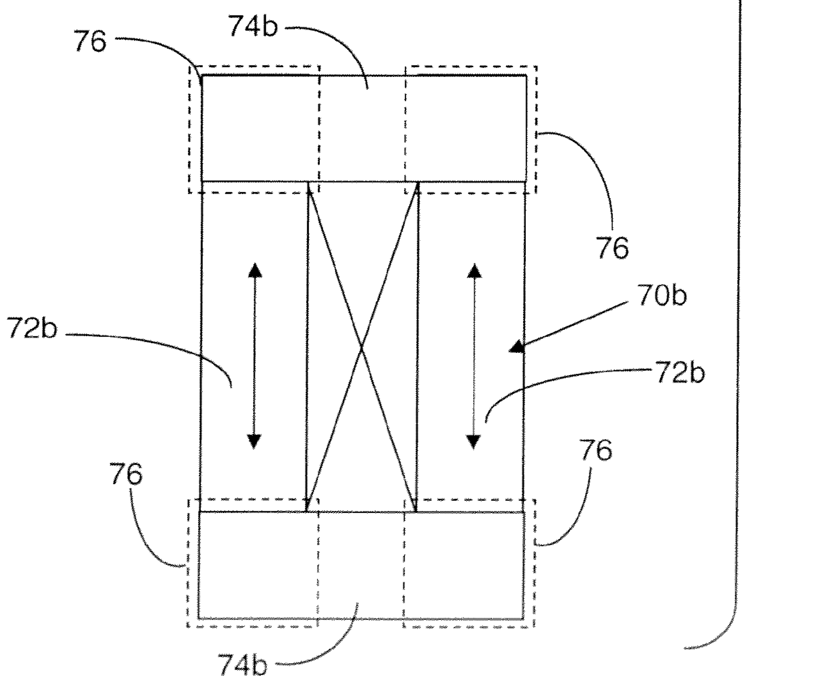


Fig. 7B

ECONOMICAL CORE DESIGN FOR ELECTROMAGNETIC DEVICES

FIELD OF THE INVENTION

This invention relates to electromagnetic devices. In particular, this invention relates to electromagnetic devices with laminated steel cores.

BACKGROUND OF THE INVENTION

Electromagnetic devices such as various kinds of transformers and reactors are widely used in power supply and distribution systems. Reduction of their cost and/or power losses can significantly improve the economic parameters of such power systems.

In electromagnetic devices, power losses in the windings are directly proportional to the square of the loading of the winding. Therefore, power losses in a winding are much lower under low load conditions than under heavy load conditions. To the contrary, power losses in the core of an electromagnetic device having a ferrous core are independent of the load, and therefore power losses do not change significantly as long as the device is connected to the power system. This can be costly, because in many applications the devices are always connected to the power system regardless of whether there is load on them or not.

Conventional methods for reducing losses in a ferrous core have involved the use of higher quality steel for the core. For example, a major advancement in core losses reduction was the introduction of cold rolled grain-oriented steel. Grain-oriented steel has a polycrystalline structure, which provides high permeability and low energy dissipation (power losses) when the magnetic field flows in the direction of the grains.

However, there are two main drawbacks in the use of the grain-oriented steel. The cost of grain-oriented steel is substantially higher than the cost of non-grain-oriented steel; and the power loss in grain-oriented steel is substantially higher when the flux is flowing perpendicular (quadrature) to the direction of the grains than when the flux is flowing in the direction of the grains. As a result, a relatively high power loss is concentrated in the corners of a ferromagnetic core where the flux direction changes and crosses the grain orientation, as illustrated schematically in FIG. **2**. The higher the grade of the grain-oriented steel, the higher is the difference between the power losses with flux flowing along the grain orientation versus across the grain orientation.

In order to reduce such power losses in the corners of grain-oriented steel cores, the prior art employed different core configurations such as mitered cores and wound distributed-gap cores. The use of a mitered core allows for some reduction of corner losses, but at significantly greater expense than a conventional grain-oriented steel core. A wound core is even more expensive than a mitered core, and in general for multi-phase devices does not result in any substantial reduction of power losses in the core.

The highest level of core losses reduction is achieved through use of amorphous steel for the core. However, the cost of amorphous steel is extremely high, and as such this core design option is not widely used.

BRIEF DESCRIPTION OF THE DRAWINGS

In drawings which illustrate by way of example only a preferred embodiment of the invention,

FIGS. **1**A and **1**B are schematic views showing layers of laminates in a prior art three-phase grain-oriented steel core for an electromagnetic device.

FIG. **2** is a schematic view illustrating a typical flux distribution in the corner of the prior art grain-oriented steel core composed of the layers of laminates in FIGS. **1**A and **1**B.

FIG. **3**A is a schematic view of a butt gap magnetic core according to the invention, having core legs made of grain-oriented steel and yokes made of non-grain-oriented steel.

FIG. **3**B is a schematic view of a butt gap magnetic core according to the invention, having yokes made of grain-oriented steel and core legs made of non-grain-oriented steel.

FIGS. **4**A and **4**B are schematic views of the layer arrangement in a first embodiment of a three-phase magnetic core for an electromagnetic device according to the invention.

FIG. **4**C is a partial perspective view of the magnetic core formed from alternate interleaving of the layers of FIGS. **4**A and **4**B.

FIGS. **5**A and **5**B are schematic views of layer arrangement in a further embodiment of a three-phase magnetic core for an electromagnetic device according to the invention.

FIGS. **6**A and **6**B are schematic views of layer arrangement in a single-phase magnetic core for an electromagnetic device according to the invention.

FIGS. **7**A and **7**B are schematic views of layer arrangement in a further embodiment of a single-phase magnetic core for an electromagnetic device according to the invention.

DETAILED DESCRIPTION OF THE INVENTION

The invention provides, for an electromagnetic device, a magnetic core formed from steel laminations, comprising a plurality of core elements, comprising at least two legs, at least two yokes, the yokes being oriented substantially quadrature to the legs, such that abutting core elements are in substantially quadrature relation, a plurality of flux deflection zones defined in regions where flux flows from one core element to an abutting core element, the core elements being formed from alternating interleaved layers, at least one of the layers comprising at least one core element composed of grain-oriented steel, and the remaining core elements being composed of non-grain-oriented steel, such that a plurality of flux deflection zones are composed of a substantial amount or substantially entirely of non-grain-oriented steel, whereby flux flowing in a direction of a grain orientation in the at least one core element composed of grain-oriented steel changes direction to flow through the abutting core element in the flux deflection zone composed of non-grain-oriented steel.

The invention further provides an electromagnetic device, comprising a magnetic core formed from steel laminations, and at least one winding wound over the core, the magnetic core comprising a plurality of core elements comprising at least two legs, at least two yokes, the yokes being oriented substantially quadrature to the legs, such that abutting core elements are in substantially quadrature relation, a plurality of flux deflection zones defined in regions where flux flows from one core element to an abutting core element, the core elements being formed from alternating interleaved layers, at least one of the layers comprising at least one core element composed of grain-oriented steel, and the remaining core elements being composed of non-grain-oriented steel, such that a plurality of flux deflection zones are composed of a substantial amount or substantially entirely of non-grain-oriented steel, whereby flux flowing in a direction of a grain orientation in the at least one core element composed of grain-oriented steel changes direction to flow through the abutting core element in the flux deflection zone composed of non-grain-oriented steel.

A magnetic core for an electromagnetic device comprises a plurality of core elements, including legs **12** and yokes **14** arranged quadrature to the legs **12**. FIGS. **1**A and **1**B illustrate typical alternating layers **10***a*, **10***b* in a prior art interleaved magnetic core for an electromagnetic device, such as (without limitation) a transformer or reactor. As is well known to those skilled in the art, an interleaved-type laminated magnetic core comprises a series of interleaved laminate layers **10***a*, **10***b* of steel laminations. Each laminate layer **10***a* or **10***b* may be formed from one laminate of sheet steel or from multiple laminates of sheet steel, depending on design parameters and the gauge of the steel. A typical magnetic core may for example have three 0.014 inch thick steel laminates in each laminate layer **10***a*, **10***b*. In the embodiment illustrated, the core would alternate between the layers **10***a* and **10***b*, in interleaved fashion, to achieve the desired core thickness. As is well known, in this type of magnetic core the joints between core elements are located in different parts of the layers **10***a*, **10***b*, so that in the assembled core with the layers **10***a*, **10***b* interleaved there is no intentional gap between the core legs **12** (formed from alternating leg components **12***a*, **12***b*) and the yokes **14** (formed from alternating yoke components **14***a*, **14***b*), which would increase the magnetic reluctance of the core.

FIG. **2** is a partial schematic view showing the layer **10***a* of the prior art laminated grain-oriented steel core of FIGS. **1**A and **1**B. In the simple case illustrated, the width of the core leg **12** and the width of the yoke **14** being equal, angle α**32** 45 degrees. It will be appreciated by those skilled in the art that the magnetic flux in the core **10** actually changes direction in a less abrupt and more chaotic pattern, and the 45 degree angle shown is an approximation for purposes of illustration only.

The flux passing through the portions of the layer **10** where the legs **12** and yokes **14** abut, hereinafter referred to as the "flux deflection zones" **16** (i.e. those regions where the flux changes direction in the core), can be represented by two components: a direct component Φd (as shown, in the direction of the yoke **14**), and a quadrature component Φq (as shown, in the direction of the leg **12**). Because the yoke **14** overlaps the leg **12** in the layer **10***a*, the direct component of the flux Φd is flowing along the grain orientation and the quadrature component of the flux Φq is flowing across the grain orientation.

Power losses created by the flow of the direct component of the flux Φd are defined in losses per pound, as specified by the steel manufacturer. However, the power losses created by the flow of quadrature component of the flux Φq, because it is flowing quadrature to grains in the steel, are much higher than nominal power losses created by the flow of the direct component of the flux Φd, which flows in the direction of the grains in the steel. For example, in M6 type grain-oriented steel, power losses created by the flow of quadrature component of the flux Φq are approximately three times higher than power losses created by the flow of the direct component of the flux Φd flowing in the direction of the grain.

FIG. **3**A illustrates a corner of a butt gap core **20** according to the invention, wherein the core legs **22** are formed entirely from grain-oriented steel and the yokes **24** are formed entirely from non-grain-oriented steel. This type of core is formed from identical layers, thus creating a joint between the legs **12** and the yokes **14**. The legs **22** are formed from grain-oriented steel while the yokes **24** are formed from non-grain-oriented steel. In such a core design the flux in the core legs **22** flows along the direction of the grain with low power losses, and flux shifting occurs in the yokes **24** which are made of non-grain-oriented steel. This design reduces core losses in the flux deflection zones **26**, since the steel in the flux deflection zones **26** is non-grain-oriented steel, and also reduces the overall cost of the core because non-grain-oriented steel is substantially less expensive than grain-oriented steel. However, the use of non-grain-oriented steel in this fashion, although reducing power losses in the flux deflection zones **26** of the core **20**, may increase power losses in the other parts of the core (specifically in this case, the yokes **24**) because power losses are substantially greater in non-grain-oriented steel than in grain-oriented steel. Reduction of power losses from the yokes **24** may be achieved by increasing the width of each yoke **24**, and the cost savings of the core **20** will still be significant, if design parameters permit this.

FIG. **3**B illustrates a corner of a butt gap core **30** according to the invention, wherein the core legs **32** are formed entirely from non-grain-oriented steel and the yokes **34** are formed entirely from grain-oriented steel. In this embodiment the legs **32** overlap the ends of the yokes **34**, and the flux deflection zones **36** are generally at the ends of the legs **32** which are formed from non-grain-oriented steel. The principles and operation of this embodiment are similar to those of the embodiment of FIG. **3**A.

FIGS. **4** to **6** illustrate various configurations of interleaved-type laminated magnetic cores according to the invention. According to the principles of the invention, the core elements are formed from steel laminate layers, the layers being composed of a combination of grain-oriented steel and non-grain-oriented steel such that the magnetic flux flows along the steel grains of grain-oriented steel within the portions of core elements in which the flux flows substantially along the length of the core element and does not change direction; while the flux deflection zones of the core, i.e. the regions of the core in which the flow of magnetic flux changes direction from a leg to a yoke or from a yoke to a leg, are composed partly or entirely of non-grain-oriented steel. This reduces power losses in the flux deflection zones **16** between abutting core elements, because the magnetic flux is never flowing quadrature to the direction of the grain orientation in the grain-oriented steel portions of the core elements. The level of core power losses can still be controlled by changing the width of the yokes and/or changing the ratio of the cross-section areas of the grain-oriented steel and non-grain-oriented steels.

In particular, FIGS. **4**A and **4**B respectively illustrate the two alternating interleaved laminate layers **40***a*, **40***b* in a three-phase magnetic core **40** according to the invention. The core **40** has core elements comprising legs **42***a* and **42***b* abutting yokes **44** arranged in quadrature relation to the legs **42***a* and **42***b*, as is conventional. However, in the first layer **40***a* of the two alternating layers, shown in FIG. **4**A, the yokes are formed from components **44***a* composed of grain-oriented steel (as indicated by the double-headed arrows) disposed between the legs **42***a*, while the legs **42***a* of the layer **40***a* are composed entirely of non-grain-oriented steel. The flux deflection zones **46** in the layer **40***a* are disposed at the ends of the legs **42***a*, and are thus composed of non-grain-oriented steel. In the second layer **40***b* of the two alternating layers, shown in FIG. **4**B, the yokes **44** are composed entirely of non-grain-oriented steel while the legs **42***b* are composed of grain-oriented steel (as indicated by the double-headed arrows) and extend between the yokes **44**. The flux deflection zones in the layer **40***b* are disposed at the ends and middle portions of the yokes **44**, and thus composed of non-grain-oriented steel. When multiple layers **40***a*, **40***b* are assembled into a core **40** in alternating interleaved fashion, the flux deflection zones **46** in the core **40** are entirely composed of non-grain-oriented steel, as shown in FIG. **4**C.

Thus, as magnetic flux flows through the non-grain-oriented steel core legs **42** and reaches a flux deflection zone **46** of the core **40**, the flux deflects toward a quadrature orientation substantially within the flux deflection zone **46**, which is composed of non-grain-oriented steel, and enters the grain-oriented steel yoke components **44***a* already substantially aligned with the direction of the steel grains. This configuration is also advantageous because the longer components in the layers **40***a*, **40***b* are formed from non-grain-oriented steel, which is less expensive than grain-oriented steel, so the cost of the core **40** relative to a conventional core having substantially the same power losses is considerably less than the cost of a comparable prior art core composed entirely of grain-oriented steel, for example up to 25% less. Alternatively, the power losses in the core **40** are substantially less than the power losses in a conventional core of the same cost as the core **40**.

FIGS. **5**A and **5**B illustrate laminate layers **50***a*, **50***b* of another configuration of magnetic core **50** according to the invention. The core **50** has core elements comprising legs **52** abutting yokes **54** arranged in quadrature relation to the legs **52**. In this embodiment, in the first layer **50***a* of the two alternating layers, shown in FIG. **5**A, the yokes **54** are formed from non-grain-oriented steel and are disposed between the outer legs **52** which are also formed from non-grain-oriented steel. Only the middle leg **52**, disposed between the yokes **54**, is composed of grain-oriented steel (as indicated by the double-headed arrow). The flux deflection zones **56** in the layer **50***a* are disposed at the ends of the outer legs **52** and the middle portions of the yokes **54**, which are composed of non-grain-oriented steel. In the second layer **50***b* of the two alternating layers, shown in FIG. **5**B, the yokes **54** are composed of non-grain-oriented steel while the outer legs **52** are composed of grain-oriented steel (as indicated by the double-headed arrows) and extend between the yokes **54**. The flux deflection zones in the layer **50***b* are disposed at the ends of the yokes **54** and the ends of the middle leg **52**, and are thus composed of non-grain-oriented steel. When multiple layers **50***a*, **50***b* are assembled into a core **50** in alternating interleaved fashion, the flux deflection zones **56** in the core **50** are entirely composed of non-grain-oriented steel. The core power losses in this option are higher than in core **40**, but the cost of this core **50** is substantially reduced in comparison with the cost of the core **40**.

FIGS. **6**A and **6**B illustrate a single-phase interleaved magnetic core **60** according to the invention, with the winding on the middle core leg **62**. The core **60** has core elements comprising outer legs **61** (typically one half the width of the middle leg **62**) abutting yokes **64** arranged in quadrature relation to the legs **61**, **62**. In this embodiment, in the first layer **60***a* of the two alternating laminate layers, shown in FIG. **6**A, the yokes **64***a* are formed from non-grain-oriented steel and are disposed between the outer legs **61***a* which are also formed from non-grain-oriented steel. Only the middle leg **62***a*, disposed between the yokes **64***a*, is composed of grain-oriented steel (as indicated by the double-headed arrow). The flux deflection zones **66** in the layer **60***a* are disposed at the ends of the outer legs **61***a* and the middle portions of the yokes **64***a*, which are composed of non-grain-oriented steel. In the second layer **60***b* of the two alternating layers, shown in FIG. **6**B, the yokes **64** are composed of non-grain-oriented steel portions **64***b* extending between a non-grain-oriented steel middle leg **62***b*, while the outer legs **61***b* are composed of grain-oriented steel (as indicated by the double-headed arrows) and extend between the yokes **64***b*. The flux deflection zones **66** in the layer **60***b* are disposed at the ends of the yoke portions **64***b* and the ends of the middle leg **62***b*, and are thus composed of non-grain-oriented steel. When multiple layers **60***a*, **60***b* are assembled into a core **60** in alternating interleaved fashion, the flux deflection zones **66** in the core **60** are entirely composed of non-grain-oriented steel.

FIGS. **7**A and **7**B illustrate a single-phase interleaved magnetic core **70** according to the invention, with windings on one or preferably both outer core legs **72**. The core **70** has core elements comprising legs **72** abutting yokes **74** arranged in quadrature relation to the legs **72**. In this embodiment, in the first layer **70***a* of the two alternating layers, shown in FIG. **7**A, the yokes **74** are formed from grain-oriented steel (as indicated by the double-headed arrows) and are disposed between the legs **72** which are formed from non-grain-oriented steel. The flux deflection zones **76** in the layer **70***a* are disposed at the ends of the legs **72** which are composed of non-grain-oriented steel. In the second layer **70***b* of the two alternating layers, shown in FIG. **7**B, the yokes **74** are composed of non-grain-oriented steel, while the legs **72** are composed of grain-oriented steel (as indicated by the double-headed arrows) and extend between the yokes **74**. The flux deflection zones **76** in the layer **70***b* are disposed at the ends of the yokes **74**, and are thus composed of non-grain-oriented steel. When multiple layers **70***a*, **70***b* are assembled into a core **60** in alternating interleaved fashion, the flux deflection zones **76** in the core **70** are entirely composed of non-grain-oriented steel.

The invention thus covers both butt gap core and interleaved core designs. It will be appreciated that the principles of the invention will apply to reduce power losses at a reduced cost even if some, but not all, of the flux deflection zones **16** are composed entirely of non-grain-oriented steel.

Various embodiments of the present invention having been thus described in detail by way of example, it will be apparent to those skilled in the art that variations and modifications may be made without departing from the invention. The invention includes all such variations and modifications as fall within the scope of the appended claims.

We claim:

1. For an electromagnetic device, a magnetic core formed from steel laminations, comprising a plurality of core elements, comprising at least two legs, at least two yokes, the yokes being oriented substantially quadrature to the legs, such that abutting core elements are in substantially quadrature relation, a plurality of flux deflection zones defined in regions where flux flows from one core element to an abutting core element, the legs being formed from alternating interleaved laminate layers, at least one of the layers being composed of grain-oriented steel, and the remaining layers of the core elements being composed of non-grain-oriented steel, such that a plurality of flux deflection zones are each composed substantially of non- grain-oriented steel layers from a leg extending substantially over an entire region where the flux changes direction in the core interleaved with non-grain-oriented steel layers from a yoke extending substantially over the entire region where the flux changes direction in the core, the plurality of flux deflection zones thereby being composed substantially of non-grain-oriented steel, whereby flux flowing in a direction of a grain orientation in the at least one layer composed of grain-oriented steel changes direction to flow through the abutting core element in the flux deflection zone composed of non-grain-oriented steel.

2. The magnetic core of claim **1** wherein all flux deflection zones are composed substantially entirely of non-grain-oriented steel.

3. The magnetic core of claim **1** wherein the core is a butt gap core.

4. The magnetic core of claim **3** wherein at least one core leg is formed from grain-oriented steel and the yokes are formed from non-grain-oriented steel.

5. The magnetic core of claim **3** wherein the yokes are formed from grain-oriented steel and at least one core leg is formed from non-grain-oriented steel.

6. The magnetic core of claim **1** wherein in a first layer grain-oriented steel yokes extend between non-grain-oriented steel legs, and in a second layer grain-oriented steel legs extend between non-grain-oriented steel yokes.

7. The magnetic core of claim **6** having three legs, wherein in the first layer the yokes comprise grain-oriented steel yoke portions extending between each outer leg and a middle leg.

8. The magnetic core of claim **1** wherein in a first layer non-grain-oriented steel yokes extend between non-grain-oriented steel outer legs and a grain-oriented steel middle leg extends between the yokes, and in a second layer grain-oriented steel outer legs extends between non-grain-oriented steel yokes portions abutting a middle leg.

9. The magnetic core of claim **8** for a single phase electromagnetic device, wherein a width of the middle leg is substantially larger than a width of the outer legs.

10. The magnetic core of claim **8** having three legs, wherein a width of the middle leg is substantially the same as a width of the outer legs.

11. An electromagnetic device, comprising a magnetic core formed from steel laminations, and at least one winding wound over the core, the magnetic core comprising a plurality of core elements, comprising at least two legs, at least two yokes, the yokes being oriented substantially quadrature to the legs, such that abutting core elements are in substantially quadrature relation, a plurality of flux deflection zones defined in regions where flux flows from one core element to an abutting core element, the legs being formed from alternating interleaved laminate layers, at least one of the layers being composed of grain-oriented steel, and the remaining layers of the core elements being composed of non-grain-oriented steel, such that a plurality of flux deflection zones are each composed substantially of non-grain-oriented steel layers from a leg extending substantially over an entire region where the flux changes direction in the core, interleaved with non-grain-oriented steel layers from a yoke extending substantially over the entire region where the flux changes direction in the core the plurality of flux deflection zones thereby being composed substantially of non-grain-oriented steel, whereby flux flowing in a direction of a grain orientation in the at least layer composed of grain-oriented steel changes direction to flow through the abutting core element in the flux deflection zone composed of non-grain- oriented steel.

12. The electromagnetic device of claim **11** wherein all flux deflection zones are composed substantially entirely of non-grain-oriented steel.

13. The electromagnetic device of claim **11** wherein the core is a butt gap core.

14. The electromagnetic device of claim **13** wherein at least one core leg is formed from grain-oriented steel and the yokes are formed from non-grain-oriented steel.

15. The electromagnetic device of claim **13** wherein the yokes are formed from grain-oriented steel and at least one core leg is formed from non-grain-oriented steel.

16. The electromagnetic device of claim **11** wherein in a first layer grain-oriented steel yokes extend between non-grain-oriented steel legs, and in a second layer grain-oriented steel legs extends between non-grain-oriented steel yokes.

17. The electromagnetic device of claim **16** having three legs, wherein in the first layer the yokes comprise grain-oriented steel yoke portions extending between each outer leg and a middle leg.

18. The electromagnetic device of claim **11** wherein in a first layer non-grain-oriented steel yokes extend between non-grain-oriented steel outer legs and a grain-oriented steel middle leg extends between the yokes, and in a second layer grain-oriented steel outer legs extends between non-grain-oriented steel yokes portions abutting a middle leg.

19. The electromagnetic device of claim **18** for a single phase electromagnetic device, wherein a width of the middle leg is substantially larger than a width of the outer legs.

20. The electromagnetic device of claim **18** having three legs, wherein a width of the middle leg is substantially the same as a width of the outer legs.

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